Flywheel Energy Storage System for Electric Start and an All-Electric Ship

John McGroarty, Jesse Schmeller, Richard Hockney, *Senior Member, IEEE*, and Matthew Polimeno

Abstract--**This paper reports on the investigation and development of flywheel technology as energy storage for shipboard zonal power systems. The goal was to determine where energy storage devices could improve operation and/or reduce life-cycle maintenance costs. Applications where energy storage can provide benefits include uninterruptible power to essential loads, "dark" start capability, load leveling, system stability and pulse weapons. A Flywheel Energy Storage System (FESS), with 25kWh of available energy, will be presented as an alternative to the current shipboard electrochemical battery system, highlighting the advantages for and challenges presented by shipboard applications.**

Flywheel technology overcomes some of the shortcomings of today's energy storage systems by having an extremely high cyclic-life, limited temperature sensitivity, no chemical hazards, charge rate equal to discharge, and reduced weight and space. As Gas Turbine Electric Starter development enters into fleet evaluation, FESS may provide dark ship start capability more so than any other systems being investigated. This paper discusses the critical technical challenges of the FESS for shipboard systems, and the steps for future development.

***Index Terms*—energy storage, composite flywheel, uninterruptible power supply, electric start, all-electric ship**

I. INTRODUCTION

The requirement for electrical energy storage is still uncertain as far as possible applications aboard an All Electric Ship. However, estimated zonal energy storage requirements have ranged from 12.5 kWh to 24 kWh **[1]**.

The Flywheel Energy Storage System (FESS) discussed herein offers several unique advantages beyond those inherent to all flywheel systems, including a self-enclosed vacuum system requiring no external vacuum components **[11][12]** thereby reducing maintenance and providing higher reliability; co-mingled rim technology **[13][14]** that stores significantly more energy, resulting in an increase in energy density; the ability to configure a number of flywheels to meet multiple power and energy requirements **[16]**; as well as tested safety mechanisms proven to ensure "loose" rotor containment.

At 25 kWh of available energy, this single system would have twice the available energy as the combined five flywheels currently being utilized in the Electric Ship Technology Demonstrator at Alstom's Technology Centre at Whetstone **[7]**. This makes the use of a flywheel much more attractive and feasible from not only a life-cycle cost perspective, but from a power and energy density standpoint as well.

The system would act as a zonal power supply unit for applications including, but not limited to, uninterrupted power to essential loads, load leveling, and electric start capability, which is currently under development, and as such will be one of the primary focuses of this paper.

A single 25 kWh system would also be another step in the development of a "rotating machine-based" system with 80 MJ (22 kWh) required for one concept for an electromagnetic (EM) rail gun **[2]**.

II. FLYWHEEL ENERGY STORAGE SYSTEMS

The FESS consists of a high-inertia composite rotor spinning on a shaft supported by magnetic bearings in a vacuum enclosure. A permanent-magnet (PM) motor is mounted on the shaft. The motor is driven with a variable-voltage, variable frequency DC-to-AC inverter. As shown in Figure 1, the natural interface to the system is a DC buss, which may be connected to a DC distribution system, or to a fixed-frequency, bi-directional inverter for connection to an AC system.

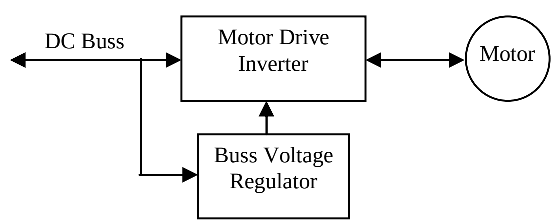

Figure 1 – Typical Flywheel Electrical Interface

Unlike a battery, which stores energy chemically, the FESS stores energy in rotational kinetic form. To charge the flywheel, current is delivered to the motor, which spins up the rotor. When the rotor reaches full speed, the FESS is fully

John McGroarty is with the Naval Surface Warfare Center in Philadelphia, PA 19112 (e-mail: john.mcgroarty@navy.mil).

Jesse Schmeller is with the Naval Surface Warfare Center in Philadelphia, PA 19112 (e-mail: jesse.schmeller@navy.mil).

Richard L. Hockney is with Beacon Power Corporation in Wilmington, MA 01887 (e-mail: hockney@beaconpower.com).

Matthew E. Polimeno is with Beacon Power Corporation in Wilmington, MA 01887 (e-mail: polimeno@beaconpower.com).

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUL 2005**	2. REPORT TYPE	3. DATES COVERED **00-00-2005 to 00-00-2005**
4. TITLE AND SUBTITLE **Flywheel Energy Storage System for Electric Start and an All-Electric Ship**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center,Philadelphia,PA,19112**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM001931. Proceedings of the 2005 IEEE Electric Ship Technologies Symposium (ESTS 2005) Held in Philadelphia, PA on July 25-27, 2005.**		
14. ABSTRACT **see report**		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

charged. To discharge, the motor acts as a generator and is driven by the kinetic energy stored in the rotor.

Through third-party testing, field trials and commercially deployed units, flywheel manufacturers have demonstrated that flywheel energy storage systems are a viable energy storage option, which is technically suited for reliable and cost-effective use in various applications. Proven power quality compensation applications range from low-power telecommunications equipment support (low kW for hours) to high-power industrial equipment support (hundreds of kW for seconds). Today's FESS combines the best features of high-speed flywheel energy storage with proven developments in high-power electronics for energy storage and delivery **[3]**.

High-speed, composite rim flywheels set themselves apart from other energy storage devices with the following characteristics:

- *20-year design life* that far exceeds the life of electro-chemical systems; when combined with no maintenance and high cyclic life results in reduced life-cycle cost.
- *Modular architecture* allows a number of flywheels to be configured to meet any power or stored energy requirement.
- *Patented Co-mingled Rim Technology* (PCRT™) that efficiently stores significantly higher levels of energy, thereby reducing size and mass, resulting in an increase in energy density.
- *Combination of active magnetic bearings, touchdown roller bearings, and momentum management techniques* to handle shipboard loads, alleviating the need for a gimbal-mount.
- *State-of-health monitoring system,* shown in Figure 2, lends itself to condition-based maintenance (CBM). Critical system parameters (e.g., bearing run-out) could be remotely monitored and variation tracked to pre-defined limits.

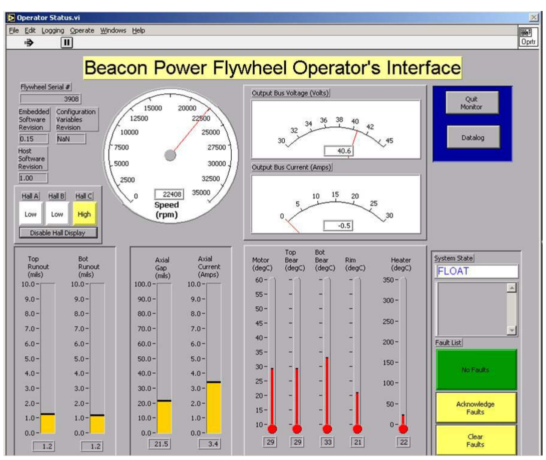

Figure 2 – State of Health Monitoring System

- *Predictable operation*, since the state of charge is precisely known at all times as a function of speed (RPM).
- *Mechanical system requires no maintenance*. Lead acid batteries represent a continuous and generally unwelcome maintenance load and have a negative impact on manning levels, workload and quality of life at sea **[4]**.
- *High cyclic life*, capable of hundreds of thousands of cycles, such that performance does not degrade due to depth, rate or frequency of charge/discharge cycles.
- *Temperature tolerant;* unlike batteries, whose performance degrades at temperature extremes, flywheels exhibit no change in capacity based on environmental conditions.
- *Increased system availability,* since flywheels are capable of charging at a rate equal to or greater than their discharge rate.
- *Low standby losses*, resulting in an increase in efficiency. Losses are defined as everything that causes the wheel to slow down with no current in the motor leads. That includes bearings, windage and motor eddy currents.
- *No need to oversize the energy storage equipment* as the flywheel capacity does not decay over time, essentially having an indefinite shelf life.
- *Green technology* results in no costs associated with hazardous chemical transport, installation and disposal.

III. POTENTIAL NAVAL RELEVANCE

Zonal power enhances the ability of a distributed system, when experiencing faults, to ensure that loads in undamaged zones do not experience service disruption. Zonal survivability can be achieved if generation or storage is in every zone **[5]**. Below are several potential applications for a FESS to support future shipboard integrated power systems.

- *Electric or "dark" start capability*. Provide enough power capability and start "opportunities" to permit a gas turbine engine to come online from the dormant state. This application is the focus of this paper.
- *Uninterrupted power to essential loads*. An early review concluded that the best energy storage device is likely to be a hybrid system of a battery and flywheel, distributed throughout the ship **[1]**. With the capability of supporting loads for several minutes instead of seconds, the 25kWh FESS may preclude the need for the batteries.
- *Single-generator operation*. Integrated Full-Electric Propulsion makes it possible to operate with a single prime mover that provides power to both propulsion and hotel loads, as long as ride-through power is available **[3]**. It has been suggested to run one gas turbine generator instead of two during routine operations by the implementation of flywheels or another energy storage device to significantly reduce fuel costs **[6]**.
- *Bulk storage*. Provide load leveling and associated frequency regulation activities, first by absorbing power when it is in abundance and then discharging the same for the desired frequency effect. The relationship between system frequency and variations and the excess or lack of real power generation at a given time can be best expressed in mathematical terms as Equation (1) **[3]**.

$$\sum P_{souces} - P_{sinks} = \frac{d\,(K.E.)}{dt} = \frac{d}{dt}\sum_i J_t\,\omega_t^2 \qquad (1)$$

where P = active (real) power (MW)
$K.E.$ = kinetic energy of system
J = rotating machine's moment of inertia
ω = rotating machine's angular velocity

Seven of the proposed FESS units would meet the requirement estimated at 1MW for 10 minutes **[7]**.

- *Pulse power loads/systems*. Two of the leading Pulse Forming Network (PFN) energy storage candidates are capacitors and pulse generators (e.g. compulsator) with flywheel energy storage **[8]**. The cyclic capability of the flywheel may also allow for recovery and re-use of energy that remains in the rails and bus work.

It may be possible to have an energy storage system based on distributed flywheel modules that can simultaneously perform <u>all</u> of these functions, rather than having each function provided separately with batteries or other limited-capability energy storage technologies.

IV. ELECTRIC START

Flywheel energy storage is being investigated as a direct result of the potential use of electric starters on U.S. Navy gas turbine engines. All current gas-turbine powered ships of the U.S. Navy use compressed air to provide start-up capability to the engines. This applies to the main propulsion plants (LM2500) as well as power generation units (501-K17/34). In order to meet air flow demands to start these engines, the complex pneumatic system increases maintenance schedules and high failure rates occur that often disrupt critical ship schedules, increase manpower allocations for its service, as well as increased engine downtime intervals. Another critical aspect of the pneumatic starter system is the ship's space committed to store pressure flasks, piping, valves, pumps, cooling devices, and other support subsystems. Traditionally, the current start systems on these engines have always been on the Navy's TMA/TMI failure list, and the recently demonstrated Electric Start System can provide the Navy with a much needed improvement. Installation of the Electric Start System will present the fleet with a simple, more reliable start system that was not available in the past. Installation of this system will assist NAVSEA in optimizing fleet readiness while reducing maintenance and manning requirements, improving equipment reliability, and reducing total ownership cost in both current and future installations.

A. Benefits

In addition to the start cycle, the Electric Start System (ESS) will be called upon to motor the engine for the purposes of water washing or other miscellaneous maintenance activities. In all cases the Electric Start Motor (ESM) will be controlled via an Electric Start Controller (ESC) using existing control signals. Another benefit of the ESS is that the ESC will provide selective control capability. For example, the ESS will be able to slowly turn the engine during maintenance inspections.

There are two features that are intrinsic to the ESS and not feasible on hydraulic or pneumatic starting systems without raising their level of complexity and cost. The first feature allows the ESS to control the rate of acceleration of the engine at startup. Therefore, the ESS has the ability to learn the specific torque curves of various engines. Thus, the same hardware may be used for different engines by changing parameters in the ESS control software. This also allows the engine to reach idle speed faster, decreasing the time needed to take a load command. It is anticipated that the ESS can provide up to 25% faster starts on the LM 2500 engine. The second feature of the ESS is that its impact torque on the engine gearbox is virtually zero. Since the impact torque is non-existent, the gearbox and ESS will have less wear and tear, greatly reducing ownership costs on these items. Also, the ESS has the ability to re-engage the gearbox at any engine speed between 0 and 4500 RPM. Since there is no impact torque, the ESS "senses" and matches engine speed within the aforementioned range and provides a smooth engagement between the electric starter motor and the gearbox. Therefore, it is not necessary to ensure that engine speed be below 300 RPM for starter re-engagement. This proves very useful in performing unlimited consecutive starts, high-speed cranks (purges), and low-speed cranks (motoring) for water washing and other maintenance operations.

Significant weight savings can be achieved using a pure ESS. It is anticipated that the electric start motor (ESM) will weigh approximately 130 pounds (for LM2500/6000) and the electric start controller (ESC) will weigh another 1200 pounds. When compared to 10,115 pounds for a typical hydraulic start system, one of the more promising benefits of an ESS becomes apparent.

Equally important are the space savings. Here again the benefits are tremendous. The footprint of a hydraulic starter "skid" (outside of the gas turbine package) is approximately 52.5 square feet. By comparison, the ESS space requirements are trivial – the space required for power and control cables is only 7.1 square feet. The minimal ESS ship interfaces result in valuable engine room "real estate" freed up for other services.

In the area of Environment, Health, and Safety (EHS) the ESS eliminates the need for hydraulic starting fluid (MIL-L-17672) and high-pressure fluid lines (up to 3000 psi (211 kg/cm2)). Each of these items has the potential for adverse effects on personnel safety and the environment. There is little starter control flexibility when using fluid systems. Hydraulic starters use a regulated oil flow that traditionally has provided for a maximum of two regulated flow quantities (normally 55 and 22 gpm (208 and 83 lpm) in the case of the LM2500) resulting in two per set rotational speeds on the engine.

As the Navy prepares to conduct a fleet evaluation of the electric starter on the LM2500 engine in FY-06, we must focus our attention on the use of the electric starter on power-generation gas turbines in both current and future use. The electric start offers many advantages to new ship platforms, not just in reduced weight and size, but it is also readily adaptable to all-electric ship architecture. The ESS Controller Unit is a programmable device and may be configured to sense and redirect its power demand to any available source. By doing this, the unit ensures that it remains operational and ready to start or crank the gas turbine engine at all times, from a variety of power sources. The use of flywheel technology as an emergency energy storage device to support dark-ship starts with the Electric Start System is the basis for this investigation.

B. Implementation

Figure 3 illustrates the typical electrical input to the ESS Controller Unit and electrical output to the Starter Unit during acceleration from start to idle. This provides information on the general behavior of the ESS and how it delivers torque to the LM2500 engine. The light blue curve is engine speed (NGG) in RPM as a function of time, while the other curves show qualitatively the input current, and output current and voltage. Review of this data allows adjustment of the ESS to provide the optimal torque at the proper time in the start sequence. This results in the fastest and smoothest starts possible without overstressing elements of the system **[10]**.

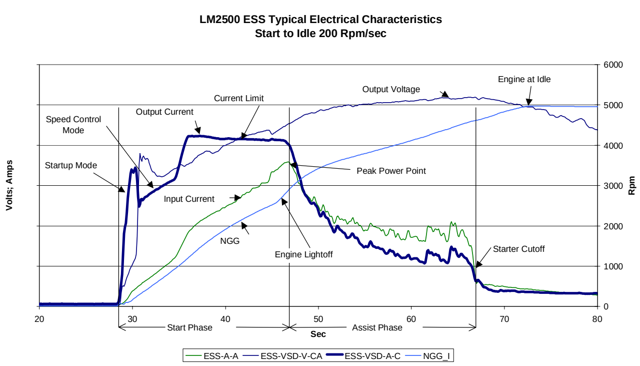

Figure 3 - Electrical characteristics during a typical engine start using ESS

Dark start capability (starting the electrical generator gas turbine with no power available onboard the ship) is a requirement for all U.S. Navy ships. In the case of the installation where the Rolls Royce 501-K17/34 engines are used, this must occur within one minute. Presently on the Rolls Royce engines, high-pressure air flasks store the air required to turn the air turbine starter on the engine to initialize the start. Current air-flask storage allows for about four attempts to start the engine before the air supply is exhausted. Installation of an electric starter will require an electrical storage device to provide the necessary energy to start the engine.

During electrical starter testing at the Naval Surface Warfare Center in Philadelphia, start requirements were recorded for starting the LM2500 engine. Figure 4 shows the input power in kW and the engine speed (NGG) in RPM as a function of time during a typical start using the electric starter; energy usage was 2.3 kWh for each normal start.

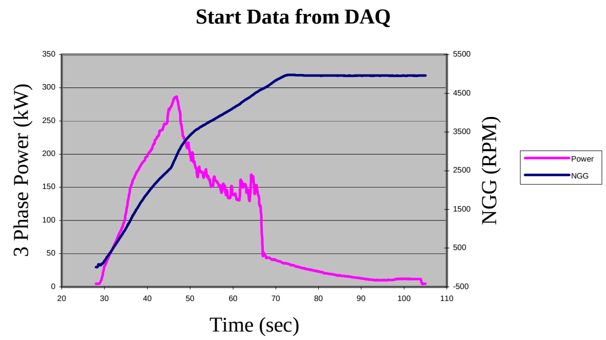

Figure 4 - Power usage during normal LM2500 start

To ensure current ship design integrity, an energy storage device must be able to provide enough electrical energy to perform four starts, thus 9.2 kWh of stored energy. The flywheel assembly investigated in this paper will provide 25 kWh of stored energy, enough to perform 10 complete start attempts, far more than is currently available. The controller units for both the starter and the flywheel make integration of the FESS very straightforward and simple.

V. PROPOSED FLYWHEEL SYSTEM

Major risk areas are shock tolerance of the flywheel **[8]** and the dynamic shipboard environment. To address the dynamic environment, pitch and roll rates will require that the flywheel's spin axis be mounted parallel to the ship's keel axis to minimize precession torque caused by roll rate. Active magnetic bearings (AMB) will be sized to handle the forces resulting from the remaining rotational and translational motions. Shock loads will be addressed with a combination of isolation mounts and momentary touchdown bearings to back up the AMB. Success criterion for the touchdown bearings is that the unit will continue to operate at full speed on the AMB after a full-shock exposure (Grade A). The primary issues are the bearing capability to withstand the dynamic loads and whether proper rotordynamic recovery can be assured. Through extensive testing, Beacon has successfully achieved system recovery from a dropped 6 kWh rotor, and will apply the analytical tools and test hardware developed there as early risk mitigation. Since the touchdown bearings are the most likely component in the system to experience unexpected failure, bearing "packages" and access covers will be designed such that these components are easily replaceable when the flywheel is at zero speed. Figure 5 highlights several features of the proposed system.

The mechanical unit is 36 inches diameter and 66 inches long, weighing approximately 3000 pounds. The electronics package is estimated at 19 by 24 by 60 inches, weighing approximately 500 pounds.

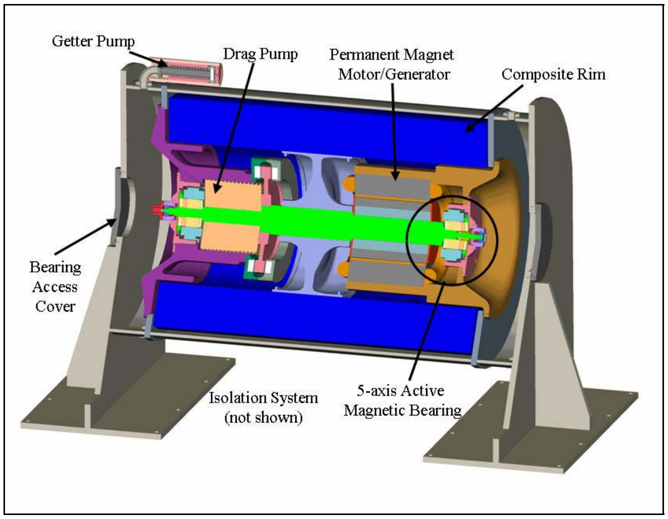

Figure 5 - Preliminary Flywheel Concept

A. System Components

1. Composite Rim

The energy storage composite rim is designed and manufactured using Beacon's patented co-mingled rim technology (PCRT™). This technique of creating several layers, each with varying ratios of glass and carbon fiber, produces an optimized stress and cost distribution throughout the part.

2. Hub

Beacon's patented metallic hub design **[15]**, in cooperation with the rim, allows operation at the highest possible tip speed for the given metal. Beacon has recently submitted a Phase II SBIR proposal to DARPA to develop a composite hub which will operate at even higher tip speed. This allows increasing the ID of the rim, which further reduces both cost and weight.

3. Motor/Generator

Beacon exclusively uses permanent-magnet brushless motors due to their high efficiency and low rotor loss. Typically, a carbon overwrap is employed to encapsulate the magnets on the rotor, which greatly increases their tip speed capability, thereby directly increasing the power density of the machine.

4. Active Magnetic Bearings

The active magnetic bearings employ five actuators and sensors to control the five degrees-of-freedom of the rotor. The sensor signals are decoupled into five axes: two each of translation of and rotation about the center of mass, and the single thrust axis. The control is fully digital with gain-scheduling employed to accommodate the gyroscopic stiffening of the rotational modes.

5. Vacuum System

Beacon's patented vacuum maintenance system uses the combination of a shaft-integral drag pump with a heated getter pump to maintain the pressure level in the rim chamber such that the drag loss is below 100 watts. The only life-limiting component is the getter material, and this is designed to be replaceable in long-life applications such as aboard ship.

6. Inverter

The motor drive inverter is primarily differentiated from standard variable-speed motor drives by the top speed (output frequency up to 500 Hz). It is Beacon's preference to co-develop the inverter with an existing supplier of variable-speed motor drives for Naval applications. We understand the challenges associated with meeting stringent EMI requirements of the Navy (MIL-STD-461), and have no desire to "re-invent the wheel."

B. Design Drivers

1. Design Impact of Ship Motion

A characteristic of composite energy storage flywheels that sets them apart from many conventional rotating machines is their large angular momentum to mass ratio **[9]**. Angular momentum, which is the product of moment of inertia and rotational speed, is the physical characteristic which turns an angular rate into cross-axis torque. Thus, the bearing load requirements for composite flywheels subjected to ship angular rates can be significant multiples of the rotor weight.

This effect for the 25 kWh rotor onboard a typical destroyer in Sea State 8 conditions (MIL-STD-1399) can be seen in Table 1. The entries are the bearing force requirements as multiples of gravity load depending on whether the flywheel spin axis is parallel to the ship's roll axis or vertical. The observation is that aligning the spin axis with the roll axis produces nicely balanced radial load requirements and reduced thrust load making this ideal for a magnetic bearing system. Contrarily, vertical alignment significantly increases both radial and thrust loads and skews the radial loading. For this reason a horizontal shaft parallel to the roll axis is the baseline.

Table 1. Bearing force requirements (g)

Flywheel Axis	Parallel to Roll	Vertical
Thrust	0.31	2.05
Radial 1	2.19	5.43
Radial 2	2.05	1.01

2. Design Impact of Ship Vibration

The vibration (MIL-STD-167-1) requirements for shipboard operation must also be assessed for their impact on the bearing system requirements. These impacts are primarily in two areas: relative motion between the stator and rotor which could cause contact; and additional bearing loads required to follow the base motion.

The assessment of these impacts is shown quantitatively in Table 2. The values are the position and acceleration responses of the magnetic bearing system to the specified base motion with a controller bandwidth of 50 Hz.

Table 2. Response to base motion

Frequency (hertz)	Gap amplitude (inch)	Rotor acceleration (g)
4	0.0024	0.05
15	0.0086	0.66
16	0.0061	0.50
25	0.0089	1.14
26	0.0046	0.61
33	0.0055	0.93
34	0.0028	0.49
40	0.0031	0.64
41	0.0019	0.40
50	0.0021	0.54

The peak gap amplitude requirement occurs at 25 Hz and is about 9 mils, safely less than the touchdown bearing clearance. The peak acceleration is at 25 Hz and is 1.14 g's which must be added to the load capability of the bearings along each of the three axes. This results in total required load capability of 3.5 g's radial and 1.5 g's axial for the bearings, well within the capability of existing technology.

3. Design Impact of Shock

The shock test requirements (MIL-S-901) must be analyzed in terms of the peak stress placed on the shaft and the touchdown bearings once the system design is completed. Since it is a brief (mS) event, it can be accommodated as long as the components can withstand the peak stress, and complete rotordynamic recovery can be ensured. Primarily, the touchdown bearings are the weak link because of the high product of pressure and velocity (P-V) stress they will experience. Beacon has experience developing these devices for earthquake environment, and will extend this knowledge to the stronger but quicker Navy shock event. Use of an isolation mounting system may be required if the peak stress is beyond that which available materials can handle.

VI. CONCLUSION

The Electric Start System for U.S. Navy marine gas turbines is becoming a reality, and will undergo a Fleet evaluation in FY-06 aboard a U.S. Navy ship. Examining the advantages of the electric start on gas turbines in the U.S. Navy shows many positive factors that can lead to reduced failures and improved reliability, providing the fleet with increased mission capability. Flywheel energy storage can provide the necessary energy to start gas turbines using the electric starter; the Beacon Power Corporation 25 kWh unit presented in this paper offers the potential of ten cold-start attempts. In addition to providing starter power, the flywheel energy storage system can be used for many other functions on an all-electric ship configuration. This paper has presented several possibilities, and also discussed some of the engineering challenges that must be overcome to ensure a reliable shipboard flywheel system.

VII. REFERENCES

Papers and Technical Reports:

[1] "Energy storage in the all electric ship"; RS Lipscombe, CP Davies, Rolls-Royce; Lt. MTW Bolton, Ships Support Agency, MoD, UK; Session 12, Paper II, All-Electric Ship Developing Benefits for Maritime Applications, Sept. 1998.

[2] "Integration of electromagnetic rail gun into future electric warships"; A Chaboki, L Thurmond, United Defense; G Grater, Anteon; D Bauer, IAP Research; F Beach, D Clayton, NAVSEA.

[3] Matthew L. Lazarewicz and Alex Rojas; "Grid Regulation by Recycling Electrical Energy in Flywheels", IEEE-Power Engineering Society General Meeting, Denver, CO, June 8, 2004

[4] "The cost benefits of single generator operation through the use of energy storage devices on warships"; RPM Hudson, CM Ross, BMT Defense Services Ltd.; Session 12, Paper I, All Electric Ship Developing Benefits for Maritime Applications, Sept. 1998

[5] "Zonal Ship Design", Capt. N Doerry, USN; ASNE Reconfiguration & Survivability Symposium, Atlantic Beach, FL, Feb.16-17, 2005

[6] "Energy Efficiency Survey Aboard USS Princeton CG-59"; A Lovins, C Lotspeich, R Perkins, J Rogers, and E Orrett, Rocky Mountain Institute, 30 June 2001.

[7] "Demonstrating Re-Configuration of Electrical Systems at the Electric Ship Technology Demonstrator"; D Mattick, M Butcher, Alstom; ASNE Reconfiguration & Survivability Symposium, Atlantic Beach, FL, Feb. 16-17, 2005.

[8] "Energy Storage for U.S. Navy Integrated Power System Applications", D. Delisle, NAVSEA; B. Desai, Consultant; H. Robey, Anteon Corp; Imarest 2003

[9] "Bearing Forces in Large Electrical Machines Under Ship Motions", Samuel Doughty, NSWC, 3rd Naval Symposium on Electric Machines, Philadelphia, PA, Dec 5-7, 2000

[10] "Test and Evaluation of a Gas Turbine Electric Starter System"; Martin Quiñones, James R. Gustafson, Kenneth A. Marks, Douglas Parsons, Richard Lapointe, Proceedings of IGTI-04, ASME Turbo Expo 2004 June 14-17, Vienna, Austria

Patents:

[11] Nathan G. Woodard and Jeremiah I. Rathburn, "Flywheel System with Parallel Pumping Arrangement", U.S. Patent 6 347 925 B1; Feb. 19, 2002.

[12] Nathan G. Woodard, Jeremiah I. Rathburn, and Paul E. Dresens, "Flywheel System with Parallel Pumping Arrangement", U.S. Patent 6 347 925 B1; Feb. 19, 2002.

[13] Ward R. Spears, "Composite Flywheel Rim with Co-Mingled Fiber Layers and Methods of Determining the Same", U.S. Patent 6 884 039 B2; Apr. 6, 2005.

[14] Ward R. Spears and Cynthia L. Shirey, "Composite Flywheel Rim with Co-Mingled Fiber Layers and Methods for Manufacturing Same", U.S. Patent 6 852 401 B2; Feb. 8, 2005.

[15] Norman C. Brackett, "Stiff Metal Hub for an Energy Storage Rotor", U.S. Patent 6 817 266 B1; Nov. 16, 2002.

[16] Richard L. Hockney, Geoff B. Lansberry, Vladislav Davidkovich, William T. Larkins, and Emil Muchnik, "Multiple Flywheel Energy Storage System", U.S. Patent 6 614 132 B2; Sep. 2, 2003.

VIII. BIOGRAPHIES

John "Jack" McGroarty graduated from the University of Detroit in Detroit, MI with a BS in Mechanical Engineering in 1976.

Mr. McGroarty began his engineering career with the US Navy as a coop student and has worked with the Navy and Gas Turbine technology for 30 years. Mr. McGroarty served as test engineer on the FFG Propulsion Hot Plant, senior project engineer on the CG-47 Gas Turbine Waste Heat Boiler testing and the Rolls Royce 501-K17 Alternate Fuels Testing. As the Life Cycle Engineer (LCE) for all US Navy Gas Turbine Generators Sets (GTGS) Mr. McGroarty became responsible for the transfer of Life Cycle Management (LCM) from Washington DC to Philadelphia. As the Program Manager for LCE/LCM efforts on GTGS Mr. McGroarty is accredited with many of the design improvements that are incorporated into the current DDG-51 Class GTGS. Mr. McGroarty is currently the Program Manager for Gas Turbine Emerging Technologies responsible for the oversight of the development of new technologies on Gas Turbine equipment like Condition Based maintenance (CBM), Electric Starter Development, Improved alloys/components to increase reliability and engine life

Jesse Schmeller graduated from SUNY Maritime College with a BE in Electrical Engineering in 1991, and from University of Missouri – Rolla with an MS in Electrical Engineering in 1994.

Mr. Schmeller taught undergraduate engineering courses related to electrical power and marine engineering for 6 years at SUNY Maritime College and at the United States Merchant Marine Academy. Currently, Mr. Schmeller is working as an Electrical Engineer in the Electrical Power Systems Section at the Naval Surface Warfare Center in Philadelphia, PA. His primary interests are energy conversion and the application of variable speed drives to auxiliary systems

Dick Hockney (M 1972, SM 1986) graduated from Northeastern University in Boston, MA with a B.S. in Electrical Engineering in 1972 and a M.S. in Electrical Engineering in 1980.

Mr. Hockney has been directing and performing flywheel-related R&D for over 20 years, including several years at the MIT Instrumentation/Draper Laboratory where he began work as a co-op student. He is a recognized expert in flywheel systems and their key components, including magnetic bearings, high-speed electrical machines, and power and control electronics. Mr. Hockney was formerly Chief Technical Officer and VP of Engineering for SatCon Technology Corporation and has been awarded 14 patents. He is a member of the Industrial Advisory Board for Northeastern University and is also a Registered Professional Engineer in Massachusetts.

Mr. Hockney is currently the Chief Engineer at Beacon Power, responsible for technical oversight of all products including flywheel energy storage systems, and Beacon's commercial line of solar power conditioning systems.

Matt Polimeno graduated from Rensselaer Polytechnic Institute in Troy, NY with a B.S. in Mechanical Engineering in 1989.

Mr. Polimeno has served in multiple roles, including 9 years at The Boeing Company specializing in composite structures including the fabrication of the DC-X's LH_2 fuel tank and the first composite fairing for the DELTA launch vehicle. Mr. Polimeno subsequently became the Manufacturing Site Manager for a $137-million program funded by NASA-Langley to development a one-piece composite aircraft wing using the stitched/resin film infusion process. Mr. Polimeno also served as Engineering Manager for Advance Storage Products, a warehouse storage racking solutions company.

At Beacon Power, Mr. Polimeno initially served as Manufacturing Assembly, Test & Quality Manager, and is currently responsible for obtaining and managing government programs.